

Annual lecture 2014 by Prof. Ashok Gadgil

The talk will revolve around the issues related to developing technology that can help improve the lives of the poor. It will draw from Prof. Gadgil's experience of developing such technology around the world such as cook-stoves for the internally displaced people in Darfur. It will also touch upon issues such as the role of Government and policy makers in enabling such technology development and its deployment to really benefit the poor.

Prof. Gadgil is the Director of the Environmental Energy Technologies Division at the Lawrence Berkeley National Laboratory and Professor of Civil and Environmental Engineering at the University of California, Berkeley, US. More information about Prof. Gadgil and his work can be found at <http://energy.lbl.gov/staff/gadgil/agadgil.html>, <http://gadgilab.berkeley.edu/> and <http://www.potentialenergy.org/>.

This booklet reproduces two papers by Prof. Gadgil about technologies he has helped to invent to help the disadvantaged. They deal with developing efficient cookstoves for the internally displaced in Darfur and removing arsenic from drinking water in Bangladesh and West Bengal.

2nd Girish Sant Memorial Annual Lecture, 2014

Improving peoples' lives by
developing and deploying
appropriate technology

Prof. Ashok Gadgil

Saturday, February 8, 2014

Girish Sant Memorial Annual Lecture

Girish Sant, a founder of Prayas and the coordinator of Prayas (Energy Group), passed away unexpectedly in February 2012. Throughout his professional career, Girish made immense contributions to the energy sector, primarily to serve the interests of the average Indian including the poor and to improve governance of the sector to prevent gross inefficiencies, earning him respect and friendship from across the spectrum. He also motivated and mentored a large number of young researchers to work in energy policy and governance issues. Several friends and well-wishers of Girish have initiated some activities in his memory to further his work of independent analysis and advocacy to promote public interest issues in the energy sector. This memorial lecture is part of these activities.

This booklet reproduces two papers by Prof. Gadgil about technologies he has helped to invent to help the disadvantaged. They deal with developing efficient cookstoves for the internally displaced in Darfur and removing arsenic from drinking water in Bangladesh and West Bengal.

Girish Sant Memorial Activities Committee

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Stove Solutions: Improving Health, Safety, and the Environment in Darfur with Fuel-Efficient Cookstoves

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In Brief

Nearly three billion people across the globe cook every day using open, three-stone fires, or rudimentary stoves that burn biomass such as wood, agricultural waste, animal dung, and charcoal. Cooking with these traditional cookstoves is inefficient and grossly polluting, harming health and the environment, and contributing to global warming. In many places worldwide, women must walk for hours to collect firewood, risking their safety and sacrificing energy and time that could be used to earn a living. While often overlooked as a major contributor to the global burden of disease, cooking over open fires indoors is the largest environmental health risk in developing countries, and exposes women (and the young children near them) to amounts of smoke equivalent to burning 1,000 cigarettes inside the home. In Darfur, Sudan, where about 2.7 million people have been displaced from their homes by conflict, the situation is particularly dire. Each day, Darfuri women face the difficult choice between risking sexual assault during treks to collect firewood or selling a portion of their family's meager food rations for cash to purchase wood. The Berkeley-Darfur Stove, developed by scientists at the Lawrence Berkeley National Laboratory (LBNL) and volunteers from UC Berkeley and Engineers Without Borders, is a metal stove that reduces the need for firewood by more than half, owing to its improved combustion and heat transfer efficiencies. LBNL has partnered with a nonprofit organization, Potential Energy, and a number of aid organizations to disseminate more than 22,000 Berkeley-Darfur Stoves to Darfuri women. Several hundred thousand more are needed.

Approximately three billion persons around the world eat daily meals cooked with fuel consisting of wood, twigs, agricultural waste, animal dung, and charcoal. They cook in diverse ways with diverse foods in diverse pots across many cultures, often on three-stone fires. A three-stone fire refers to three stones placed on the ground, supporting a pot under which a fire is lighted. Cooking with these traditional cookstoves is mostly inefficient and grossly polluting. Exposure to smoke from traditional cookstoves and open fires causes four million premature deaths annually (eight per minute), and is the largest environmental threat to health in the world today, measured in disability-adjusted life years.¹ Women and newborn infants kept close to them are at the greatest risk, as the women spend countless hours tending to these polluting stoves. Cook-fire smoke contributes to a range of chronic illnesses and acute health impacts such as early childhood acute lower-respiratory infections (including pneumonia), which lead to mortality, low birth-weight, and associated long-term adverse health impacts. For adults, the smoke can lead to risks and mortalities from lung cancer, emphysema, chronic obstructive pulmonary disease, cataracts, and bronchitis. According to public health researchers, "A fire in the kitchen, if you're cooking a meal, produces about the same pollution per hour in a typical house as a thousand cigarettes burning."²

Reliance on low-efficiency ways (e.g., three-stone fires) of using biomass for cooking and heating also forces women and children to spend many hours each week collecting wood. In humanitarian displacement settings such as Darfur, women face severe personal security risks when they collect fuel and some must trade their food aid rations for cash to purchase wood.

Lastly, residential biofuels' contribution to the total sunlight absorbing black carbon (BC) emissions is substantial, comprising 63 percent of the total BC emissions from India, 30 percent from China, 67 percent from Africa, and 33 percent globally.³ Thus, airborne pollution from biomass cookstoves contributes significantly to indoor air pollution locally, and also to global warming. BC particles in the atmosphere absorb solar radiation and reduce the sunlight reaching the planet's surface. This absorbance directly heats the atmosphere, and also produces solar dimming as observed from the planet's surface. This dimming reduces surface evaporation and atmospheric moisture. This atmospheric BC effect has been shown to reduce precipitation in some areas.⁴ Overall, BC has emerged as an important contributor to global warming. Recent studies estimate it is responsible for 18 percent of the planet's heating overload (technically called climate forcing), compared

with 40 percent contribution from anthropogenic carbon dioxide.³ Studies have also shown that BC deposition on snow and ice increases their rate of melting.⁵ There is increasing concern that BC-induced melting may contribute to the depletion of fresh water reservoirs stored in mountain glaciers and snow packs. Due to the short atmospheric lifetime of BC particles (a few weeks compared to a lifetime of about a century for CO₂), reducing emissions of BC can immediately mitigate global warming and lessen impacts on water resources.

Darfur, Sudan

Reliance on biomass for cooking has created a particularly acute situation in Darfur, where conflict has claimed the lives of at least 300,000 people and driven as many as 2.7 million more from their homes, making them refugees in their own country.⁶ These internally displaced persons (IDPs) have settled in displacement camps throughout the arid region, where they receive food aid and cooking oil from humanitarian aid organizations. However, IDP households are still responsible for gathering firewood as fuel for cooking. Because of the desert-like terrain and the large concentrated populations of the IDP camps, wood is scarce. The burden of collecting firewood falls almost entirely on Darfur's women and girls. Females in the IDP camps must walk up to seven hours three to five times a week to find a single shrub. During these treks outside the camps, women are often assaulted. While the incidence of assault is not fully known, international aid organizations have estimated that 82 percent of all attacks against women and girls occur when the victims are outside the camps, often collecting firewood.⁷

In some parts of Darfur, areas around the camps have become so denuded that it is nearly impossible to find any biomass for cooking fuel within a day's walk. In these areas, women purchase firewood from vendors who transport it to the camps and towns on trucks. Our 2010 survey of one camp in Darfur, Zamzam, showed that 80 percent of women there purchase, rather than collect, their firewood. A full 100 percent of firewood purchasers reported having to trade some of their food rations for fuel in the last food distribution. In this context, an appliance that reduces the need for firewood is of great value.

Our Solution

Late in 2004, Ashok Gadgil, senior scientist at the Lawrence Berkeley National Laboratory (LBNL), was asked by the Office of Foreign Disaster

Assistance at the United States Agency for International Development to help find a solution to this grave problem facing Darfuri women and girls. On collecting data and studying the problem, he had developed a strong hunch by the summer of 2005 that fuel-efficient stoves would be a feasible approach to provide relief to Darfur's displaced women and girls. After another few months to raise funds, arrange logistics, and train for the visit, Gadgil led a team of LBNL scientists on a fact-finding mission to Darfur in November of 2005. The team systematically collected information from displacement camps in North and South Darfur about food, cooking methods, fuel use, fuel gathering activities, the feasibility of manufacturing stoves locally, and relevant aspects of the culture with respect to cooking and stove usage.⁸ The three-stone fire was found to be the vastly predominant method of cooking, a finding that highlighted the potential to reduce fuelwood consumption (and the correspondent need to purchase or collect fuelwood) by introducing a fuel-efficient cookstove. The three-stone fire is the least efficient way to cook, with typical efficiencies of 5 to 6 percent, owing to incomplete combustion and ineffective heat transfer to the pot.

The team collected user assessments of four different types of existing improved cookstoves, including the mud stove ubiquitous in Darfur. After demonstrations, systematic key informant interviews, and efficiency tests, a metal stove from India (the Tara stove, designed by Development Alternatives in Delhi India) was determined to be, on the whole, the most liked, most efficient, and most appropriate for Darfur. While the Tara was deemed the best fit, it required further modification to suit the food type, cooking style, pot shapes, and environmental conditions in Darfur.

The stove, now called the Berkeley-Darfur Stove (BDS), has undergone 14 iterations since that initial fact-finding mission, each further tailoring it to meet Darfuri women's needs. Scientific and technical staff at LBNL and University of California, Berkeley students designed and tested each iteration, with design advice from the San Francisco professional branch of Engineers without Borders. Recognizing that the smartest scientific efforts are worthless unless the users accept the improved stove, the team worked hard to keep the users at the center of testing, redesign, and implementation. The team also worked hard to make the stove easy to assemble without mistakes, moving all the complexity in the stove design away from final assembly, so the final assembly could be performed by IDPs using relatively simple equipment. The stove is customized to fit the two most common sizes of round-bottomed pots found in Darfur, and the metal sheet used for baking a

traditional bread called kiswa. The engineers added feet, through which stakes can be easily driven into the sandy ground, fully stabilizing the stoves during the vigorous stirring necessary to make the local assida porridge. This user-centered design approach has ensured that the stove meets women's needs, which has led to high adoption rates. A 2010 independent survey found that women who have received the Berkeley-Darfur Stove now use it to cook all of their meals, and have ceased cooking over an inefficient three-stone fire,⁹ and an internal impact evaluation survey found a 100 percent adoption rate eight months after distributing the Berkeley-Darfur Stove to 100 IDP women in Zanzam camp.¹⁰

The Field of Stoves

For decades, development professionals and engineers have attempted to mitigate the health effects of cooking with biomass fuel by providing families with fuel-efficient stoves. There were two notable waves of interest in fuel-efficient stoves, one in the 1970s and another in the 1990s. However, few of these projects have seen sustained support over long periods and there are few success stories to discuss. A flaw of these projects has been the singular focus on the engineering of the stoves, with insufficient emphasis on other parts of the value chain, especially marketing and distribution. Another common flaw has been relative inattention to independent third-party impact assessment and user feedback. In addition, few fuel-efficient stove projects have considered factors that affect the likelihood of adoption of new technologies by the poor, which has been outlined by Xander Slaski and Mark C. Thurber, of Stanford University's Program on Energy and Sustainable Development: inherent motivation (connected to the perceived value of the product), affordability, and magnitude of behavior change required.¹¹ Viewed through this lens, it is not difficult to understand why cookstove projects, particularly those in rural areas, have encountered limited success. Fuel-efficient stoves face all three challenges to adoption: they are expensive, require behavior change, and are not initially valued (despite very substantial health benefits) by users in places where wood is cheap or often easy to come by. This framework suggests that cookstove projects might fare slightly better in urban areas, where users are more likely to have access to financing and to attribute an inherent value to stoves (prior to social marketing campaigns) because of the higher cost of firewood that is not freely collectible locally.

In most of Darfur, fuelwood is inaccessible or practically nonexistent within

walking distance—people pay too high a price or risk their safety to collect it—so a stove that reduces wood consumption should be a precious commodity. Slaski and Thurber have studied the barriers to adoption of advanced stoves by the poor. In their framework, cookstoves in Darfur would fall in the same category as malaria nets and fertilizer (valued, expensive, requiring behavior change). Given this analysis, we believe there is potential to create a robust market for fuel-efficient stoves in Darfur if financing is available, and the behavior change required is minimized.

In the arid, sunny camps of Darfur, introducing solar cookers might seem like the perfect way to ease the risks and burdens of burning firewood, but they do poorly at cooking local foods. A solar stove is more like an oven than a stove—it works best with food that is cooked slowly over several hours with no stirring (such as rice). In Darfur, traditional meals are continuously and vigorously stirred over high heat. The promotion of solar ovens would require a complete change of cooking styles, food eaten, and available ingredients—a logistical and social-psychological feat. In addition, solar ovens cannot be used to cook a morning meal (because there is not enough sun), and this meal would still require fuelwood. Given the low durability of low-cost solar ovens (most of those being promoted in IDP camps were made of cardboard), and the comparable amount of fuelwood that could be saved, it is clear that sturdy and durable, metal, fuel-efficient cookstoves that preserve cooking traditions are more likely to be integrated into Darfuri households.

It is worthwhile to briefly mention another important issue in thinking about locally appropriate biomass stoves. In the field of fuel-efficient stove design and production, there is a perceived tension, and oft-discussed trade-off, between “scalable” and “locally appropriate.” On the one hand, proponents of locally made, simple technologies argue that these appliances will be better liked by users because they are familiar and do not require much behavior modification. On the other, mass manufacturers contend that localized efforts to create different stoves for different populations are not easily scalable and thus will make an insignificant dent in reducing adverse impacts for the world’s population that cooks with inefficient stoves using biomass. These mass manufacturers advocate a standardized stove design that is “good enough” for most potential users, in order to reach more people. We argue that our strategy takes the best of each approach: it is both tailored for conditions in Darfur, and easily produced on a mass scale.

Atima’s life was a struggle from the beginning. Her father died before she was born, leaving her mother to raise Atima and her siblings alone. When Atima was a teenager, the Darfur conflict began and the Janjaweed militia attacked the village next door. Atima fled and for two years she was on the run, scared for her life. Finally, she made it to a town in North Darfur where she married and had four children. But her life was still a struggle, a struggle to feel secure in a hut built on land she doesn’t own, a struggle to feed her children without outside assistance.

The good news is that Darfur Stoves Project has helped to make Atima’s days easier. Before receiving her Berkeley-Darfur Stove, Atima spent hours each day cooking over a smoky fire and used half of her family’s meager income to purchase firewood. Atima’s fuel-efficient stove uses less than half the amount of wood than that smoky fire, which saves her money. It also saves her lungs, by reducing her exposure to harmful pollutants. Plus, Atima’s new stove cooks meals almost four times faster than an open fire, which gives her much more time to learn skills and earn a living. Displaced women like Atima are unlikely to go home any time soon. While it may feel like we can’t do anything about the Darfur conflict, we each have the power to make life better for women in Darfur.

In 2010 the Berkeley-Darfur Stove was tested by the Environmental Protection Agency and was found to have the highest thermal efficiency of the natural draft stoves in its cost bracket.¹²

Design and Manufacturing

An earlier prototype of the Berkeley-Darfur Stove was locally made through hand cutting metal sheets and spot welding them together in Nyala, South Darfur. This production was organized by the nongovernmental organization CHF International. Approximately 6,700 stoves were made in the CHF shop between 2007 and 2009. However, the production capacity of this shop was limited, and quality was inconsistent. Since those early days, the Darfur Stoves Project has gradually upgraded its supply chain, which is now capable of mass production and good quality control.

Today, the stove design is stamped and cut into flat sheets of metal at a workshop in Mumbai and shipped to Darfur, where these flat-kits are

assembled into stoves in a workshop that employs 12 residents of a nearby displacement camp. Manufacturing the stove components in India enables us to produce stoves much more rapidly, and for much lower cost, than if we made them entirely in Sudan or any nearby country. Faster, cheaper production means we can help Darfuri women on a large scale.

This flat-kit approach allows for an easy transition from the current small-scale, semi-manual operation to large-scale manufacturing and assembly. The main components of the stoves are designed to use only straight sheet metal cuts and folds. Such a design provides flexibility in parts manufacturing: at the lowest technology end of the spectrum, parts could be fabricated manually at 3,600 stoves per year and, at the high technology end, the parts can be stamped using a fully automated punch press machine at a rate of one set of stove parts every five to ten seconds, or approximately one million units a year, assuming single shift operation. Our manufacturer currently uses hydraulic punch presses that are manually fed and operated, providing a maximum annual production rate of 60,000 units with a single shift on a single production line.

Stove assembly is also designed for scalability by eliminating the need for advanced tools. At the small-scale end of the spectrum, a single individual operating hand tools without electricity can assemble stoves. At the large-scale end of the spectrum, an assembly shop would have 100 specialized workers organized into efficient assembly cells and would include powered assembly tools, conveyor systems, and automated quality control. The Darfur stove assembly shop currently employs a dozen workers using mostly hand-powered tools and has an output capacity of 26,000 units per year. Large-scale assembly of up to 200,000 units per year can be achieved through a combination of additional assembly shops, upgrading the existing site with more advanced assembly tools, and expanding staff size to enable greater task specialization. It now costs about \$20 to provide a stove to a user in a North Darfur IDP camp, including the cost of transport, distribution, and training to use the stove (the unit cost varies somewhat with prices of steel, shipping, etc.).

Distribution Model

To simplify and speed up delivery during the Darfur humanitarian crisis, the more than 22,000 stoves distributed to date have mostly been given free of charge to IDP women. However, as Darfur slowly moves from relief to recovery, we are beginning to explore more sustainable, market-oriented

approaches to distribution. The conflict-affected population of Darfur includes IDPs in displacement camps, IDPs in mixed (i.e., IDP/host) communities (rural and urban), and rural and urban (non-displaced) residents. Most of the 22,000 stoves distributed to date have been to IDPs within the camps. However, IDPs and non-displaced residents living in the rural and urban areas have also had their livelihoods stripped by the conflict and they, too, merit assistance. Because markets outside the camps are more established than those within them, we are beginning our first efforts at selling the stoves in these markets. In 2011 we began a small-scale marketing trial with our local partners to begin selling the stoves via existing Women's Development Associations in the town of El Fasher and several villages in Darfur. Leveraging these existing structures is cost effective and will enable us to rapidly penetrate the market. Many of the Women's Development Associations have experience with savings programs, having worked many years with other international NGOs. In the long term, we plan to fully replace free distribution with a commercial model, even within the camps.

In designing the marketing trial, we have taken care not to lose our focus on the extreme poor. We have identified and have tried to tackle the most significant barriers to technology adoption by the poorest:

- the major behavior change required to use the technology
- lack of product availability in the market
- lack of liquidity
- fear the product will not do what it says
- fear the product will break

We have addressed the first challenge by employing a user-centered design approach that allows women to preserve their cooking traditions, minimizing the behavior change required. We will continue to address the challenge of market availability through supply chain upgrading.

The remaining three challenges will be addressed by novel contracts.

First, we will address customers' lack of liquidity through a rent-to-own model. Every customer will be given a savings box where they will put their fuelwood savings (nearly \$1/day). They will pay back a small portion of the savings each week until the full cost of the stove is repaid. With this payment structure, the customer bears no financial risk.

Second, to counter fears that the product will not do what it says, we will offer a free trial period, so women can see for themselves how the stove

cooks faster, uses less wood (saving money), and produces less smoke than what they are used to.

Finally, we will alleviate concern that the product will break by allowing customers to return the stove and stop future payments.

A study testing these novel contracts in Uganda found them to be instrumental in selling stoves.⁹ More than half of the first 200 households randomly offered the novel contract accepted the free trial. In contrast, less than 5 percent of the 200 households offered the traditional (i.e., single up-front payment, no free trial or warranty) contract bought one, although most customers were given a week if they wanted time to gather funds. In addition, only 5 percent of those who accepted a free trial have returned the stove. Although there were some late payments, the rate of payments was high. Fewer than 2 percent of consumers have moved away, and another 3 percent have refused to complete payments (and even they made some payments). The study concluded that, "the novel contract appears to be a viable business model in settings where consumers purchase fuel."¹³

There is direct evidence for repayment in another stove project in North Darfur, being implemented by Practical Action (PA). The project has sold more than 3,000 liquefied petroleum gas (LPG) stoves on credit since 2007 and reports a 93 percent repayment rate. The project sells stoves via Women's Development Association Networks and requires a 20 percent down payment, followed by nine monthly installments.¹⁴ The model we are currently testing in our market trial was informed by PA's experience and has a similar repayment schedule. (However, our project uses an efficient wood-burning stove instead of the LPG stoves because the LPG stoves are two to four times the price of the Berkeley-Darfur Stove and the supply of LPG to Darfur is inconsistent.)

Promotional messages focus on money and time saving, with slogans such as, "Don't burn your money, buy the five-minute stove," replicating a similar promotional approach used by Toyola Enterprises in Ghana with marked success. In addition to traditional promotional channels, such as radio and signs, we will include the community in interactive marketing approaches, such as fuel-efficiency cooking competitions and stove demonstrations.

We are already seeing evidence of strong demand from women willing to pay for the stove. Some of the stoves distributed for free in 2010 were found in camps far from the distribution site and, upon inquiring, we learned these stoves had been sold at prices ranging from 45 to 60 SDG (US\$17–23 using the exchange rate at the time). In addition, upon announcing our marketing

trial of 500 stoves at a price of 45 SDG (if paid in four installments) or 40 SDG (if paid in one single installment), we immediately sold out and developed a waiting list of customers for the next shipment. We aim to distribute at least 10,000 stoves in Darfur in 2013, and to sell the vast majority of these.

Measuring Impact

Laboratory test results for efficiency, emissions, and time to cook. Scientists at LBNL tested the stove prototype and three-stone method for efficiency and emissions using a surrogate cooking task intended to simulate the cooking of assida, a common food in Darfur. The cooking task involves bringing to boil 2.5 liters water from room temperature, and simmering it for an additional 15 minutes. The time to heat water to boiling is faster with the BDS design at 5.8 C/minute, as compared to the TSF design at 3.6 C/minute. The three-stone fire consumed on average 564 grams of fuelwood in this task. The stove consumed on average 368 grams of fuelwood, for a savings of 35 percent compared to the three-stone fire. The carbon-monoxide emissions from the BDS for the same cooking task were only 59 percent of that of the TSF stove. Thus the BDS emits less carbon-monoxide than the savings in fuelwood. The BDS also emitted 23 percent less black carbon than the three-stone fire.¹⁵ These laboratory tests were conducted indoors in quiescent ambient air, different from the strong breeze common in displacement camps six months of the year. This might explain the larger fuel savings found in the field survey (below) than in the lab measurements.

Field impact assessment surveys. In 2010 we conducted a baseline survey of 100 households using TSF stoves for cooking in North Darfur's Zanzam camp, and a follow-up survey eight months after the women had switched to using BDS stoves for cooking. We found 100 percent of households using the Berkeley-Darfur Stove at the follow-up visit, and 44 percent of households using the Berkeley-Darfur Stove exclusively. The remaining 56 percent reported using the Berkeley-Darfur Stove alongside their open fire or rudimentary mud stove. Further research is being conducted to understand the extent to which (and the reasons why) women employ this practice of "stove stacking," in which the old method of cooking is not entirely displaced by the new technology.

Even with more than half of the families still using the traditional three-stone fire or mud stove on occasion, the result of incorporating the Berkeley-Darfur Stove into the mix was dramatic. There was no change in fuelwood

prices during this interval. Results showed that on average the fuel spending of the 100 respondents was initially 49 percent of their non-fuel spending, which dropped to 20 percent of their non-fuel spending on using the Berkeley-Darfur Stove, a reduction of more than 50 percent. The survey showed that each \$20 stove puts approximately \$354 a year into the pockets of the women using the stove or \$1770 over five years, the estimated stove life—noticeably more than our earlier lab-based estimates.

We conducted the same survey in another IDP camp (Abasi camp, in the Mellit area), farther from the region's capital of El Fasher, and found a similar impact. Forty Berkeley-Darfur Stove users were surveyed at the baseline and again eight months later. Results showed that this group reduced its spending on fuelwood from 65 percent to 31 percent of their non-fuel spending (using the BDS), again a reduction of larger than 50 percent. One hypothesis for the larger relative proportion of total expenditure devoted to fuel wood purchasing is that this area is closer to farmlands, so less funds are spent on food, while wood is nearly as scarce as it is near the more populated Zamzam camp, which lies close to North Darfur's capital.

In both locations, we found a 50 percent decline in firewood collection among the survey sample. That is, 50 percent of respondents reported fully switching from collection to purchasing their wood eight months after receiving their BDS. However, because of the small number of cases this represented, further research is being conducted to determine attribution.

Role of Partnerships

Originally started largely as a volunteer effort among scientists and students at LBNL and the University of California, Berkeley, today the Darfur Stoves Project has become the flagship initiative of an independent, nonprofit organization, Potential Energy (PE). Gadgil and several colleagues in the “pro-poor” innovation field founded Potential Energy in order to institutionalize the serendipitous process by which good ideas are conceived, developed, and brought to market in areas of the world most affected by poverty and conflict. The PE founders saw that had it not been for the passion and persistence of motivated individuals, this life-transforming technology would have lingered in the “valley of death.” PE is a uniting force that helps unleash the full potential of the many groups working to help poverty-affected people: engineers, NGOs, and distributors. While many organizations exist to disseminate technologies to poor people in developing countries, we are showing how a new and different model can work. A small project-

management organization, such as PE, acts as a technology disseminator, and the bridge between the technology research and development (in this case, LBNL) and the field. This arrangement allows for specialization of expertise and labor, greater efficiency, and an ability to scale to reach millions of people. PE currently partners with Oxfam America, Plan International, and the local Sudanese nonprofit organization, Sustainable Action Group, to assemble and disseminate the stoves in Darfur. PE also organizes and supervises flat-kit production and shipping from Mumbai to Sudan. PE maintains strong ties to LBNL to ensure a tight feedback loop between the end user and the science.

Potential Energy and the Lawrence Berkeley National Laboratory are members of the Global Alliance for Clean Cookstoves. Launched in 2010, the Global Alliance for Clean Cookstoves is a public-private initiative to save lives, improve livelihoods, empower women, and protect the environment by creating a thriving global market for clean and efficient household cooking solutions. The Alliance aims to foster the adoption of clean cookstoves and fuels in 100 million households by 2020. The United Nations Foundation hosts the Alliance's secretariat, working with more than 400 partners and 37 national governments.

Carbon Finance

We are securing financing to become certified to sell carbon credits and leverage carbon markets. Carbon markets are formed when some sort of regulatory ceiling or cap on emissions is put in place, and trading of emissions under the cap is allowed. Setting a fixed number of tons of carbon (or, in most cases, carbon dioxide) that can be emitted and allowing those tons to be traded gives a value to each of those tons as they are bought and sold to enable market members to meet their regulatory targets. Carbon trading happens when market members that can cheaply and easily reduce their emissions below their limit do so and then sell any extra allowable carbon dioxide emissions (the difference between their actual and allowed emissions) to other market members for whom it is too difficult or expensive to meet their own targets. In this way, the aggregate number of tons of carbon dioxide from all market members stays below the emissions cap, but the flexibility that results from the market means that not every member must make significant reductions. Those that can will have incentive to reduce as much as possible to earn more emissions to sell. The Kyoto Protocol greenhouse gas (GHG) emissions cap that went into effect in 2005 enabled the creation of markets in which the right to emit tons of carbon dioxide equivalent can

be bought and sold.

Since one Berkeley-Darfur Stove has the potential to save up to two metric tons of CO₂ emissions annually, each stove has the potential to sell two carbon credits every year. The money from the sale of carbon credits will be reinvested into the project and further drive expansion.

Looking Ahead

As of December 2012, more than 22,000 stoves have been distributed in Darfur, helping more than 120,000 women and their dependents, with a worth of more than \$32 million to their recipients. There are more than 400,000 displaced families in Darfur. So, we have a good start, but a lot more remains to be done. For Darfur IDPs, we have addressed well the technology design, fabrication, supply-chain, and assembly issues. We are rapidly increasing efficiency and sustainability of our distribution channels. The current bottleneck is in raising funds (either directly ourselves or through our NGO partners) to increase the reach and rate of stove dissemination in Darfur IDP camps.

Since Darfuri and Ethiopian cooking styles are similar in many ways, we have started exploring Ethiopia as a possible new market for cookstoves, and initiated plans to implement a pilot project there in 2012. In the recent past, the U.S. Department of Energy and World Vision (a large global NGO) cofunded an effort at LBNL to redesign and test the Berkeley-Darfur Stove for Ethiopian cooking conditions and preferences. Ethiopia has rapidly depleted its forest cover from 50 percent in 1950 to about 5 percent in 2005, and even now 80 percent of the households rely on biomass for their cooking fuel. Thus, the situation is close to desperate, and fuel-efficient stoves can produce immediate and much-needed relief. At the current rate of deforestation, it will take only 27 years before the country is totally deforested.

Researchers at LBNL and UC Berkeley are studying small devices called stove use monitors and plan to mount these small self-contained devices on Berkeley-Darfur and Berkeley-Ethiopia Stoves to monitor and record time-stamped stove temperature data over several months of use. Periodically, a researcher in the field using a personal digital assistant (PDA) or laptop computer will retrieve this information. The stove use monitors will enable us to have a better understanding of how cookstoves are used. Information collected will be anonymized and analyzed to understand the frequency of

stove use, the burn time for each use, and the rate at which cooks were feeding firewood into the stove during each burn. Likewise, the data will help reduce uncertainties regarding the reduction in greenhouse gas emissions from the use of improved cookstoves, and thus support obtaining carbon-offset prices for the stoves.

Further resources about Darfur Stoves Project as well as updated news of its progress are available online at www.potentialenergy.org

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Addressing Arsenic Mass Poisoning in South Asia with innovative technology and its social embedding

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In Brief

In the past two decades, arsenic-poisoning has unfolded on a vast scale in Bangladesh and West Bengal populations. WHO has correctly called this poisoning of about 70 million people the largest mass poisoning in the history of mankind. A recent (2010) study in Lancet estimates that more than 20% of adult deaths in Bangladesh are attributable to consequences of arsenic poisoning. The poisoning arises from very high concentrations of naturally occurring arsenic in the ground water, which is being used for drinking via the more than ten million hand pumps fitted on shallow tube-wells. Despite knowledge of this tragedy for the past 20 years, less than 1% of the affected population has access to arsenic-remediated water for drinking. This paper describes a technology invented in Berkeley for locally affordable and reliable arsenic remediation of this ground water, and its field trials in West Bengal, India. It also describes the critically important social science context of the steps being taken, in parallel with the field trials, to enable the indigenization of the technology and its social embedding among the stakeholders for its eventual success in the real world.

Introduction and Background

About 100 million people in Bangladesh and nearby West Bengal (India) are now exposed to very high levels of naturally occurring arsenic in the groundwater, which is their only safe water source for drinking. This has been rightly called the largest case of mass poisoning in the history of mankind (National Geographic, 2003). The World Health Organization recommends a maximum contaminant limit (MCL) for arsenic in drinking water of 10 µg / liter, while the individuals in the exposed populations are drinking water with arsenic as high as 800 µg / liter. Recent research indicates that chronic arsenic exposure is the underlying cause of about 20% of adult deaths in Bangladesh (Argos 2010). Despite public knowledge of arsenic-bearing drinking water in rural West Bengal and Bangladesh being widely known for the past 20 years, less than 1% of the exposed population has access to arsenic-remediated drinking water.

This paper introduces a novel technology (ECAR) being developed for affordable and robust arsenic remediation of real groundwater in Bangladesh and West Bengal, and describes current parallel efforts to socially embed the technology as it matures towards delivering a commercially available community-scale safe drinking water service-center.

Need for Socio-Technical System Transition

There is urgent need to make a system transition (i.e., a coherent change) in social practices and invention and deployment of new technology (Grin et al. 2011), in response to the very grave problems confronting arsenic affected villages of West Bengal. These villages face water and health crises on top of their overall poverty and malnutrition (Roy 2008). In the current situation, we expect the crises to worsen and this can lead to profound social tensions and turmoil. The need for rapid but lasting solutions, rather than short term fixes, is urgent. The system transition encompasses technology invention and innovation (new technologies, and resulting commercially available products and processes), their selection and adoption by consumers (integration in user practice), and the broader process of social embedding (e.g., regulation, markets, infrastructures and cultural symbols) (Geels and Schot 2011). "Users" in a social context give life to inventor's creativity expressed through design of a piece of hardware/equipment commonly called "technology." This should in no way give an impression that we are outlining a simple linear two social actor model: inventor invents and user uses. There

are multiple actors in any social context who act and react through their decisions to create a sequence of events and the resultant "process" (Abbott 1992), which finally determines the outcome in favor or against a new technology and its role in transition from the incumbent socio-technical regime.

Incumbent Socio-technical regime: Process Tracing

Independent researchers detected arsenic in groundwater of West Bengal as early as 1983. In most areas, this groundwater remains the main source for drinking and irrigation. Subsequently, numerous reports across multiple disciplines concluded that clinically and sub-clinically affected population are spread over at least 50% of the districts in West Bengal (Dang et al. 1983; Garai et al. 1984; Guha Mazumdar et al. 1984; Chakraborti and Saha 1987; Guha Mazumdar et al. 1988; Chakraborti and Samanta 1996; Smith et al. 2000; Guha Mazumdar 2001). The source of arsenic is naturally occurring arsenic-bearing sediments in the surrounding rock, though the dominant mechanism by which arsenic becomes mobile in water is still being debated in the scientific literature. New water sample surveys continue to reveal additional aquifers (Sengupta 2006; Das 2011) with arsenic concentration above 50µg per liter. At the least 36% of West Bengal population is at elevated health risk from arsenic exposure. Public demand for arsenic safe water to attain better health has emerged through various forms of public grievances and social conflicts between local inhabitants and the Government. The local communities have staged mass deputations to the government officials, and expressed their strong dissatisfaction by various methods including hunger strikes, rallies, and even boycotting of government campaigns for polio vaccination. New media have occasionally reported on morbidity and mortality incidents, written editorials, and published expert interviews, all to draw the government's attention and raise public awareness about the health impacts emphasizing the need for special and urgent action for a lasting solution. Economists initiated major research projects on cost of arsenic to West Bengal, and research publications, (e.g., Roy (2008)) show the benefit to West Bengal of social embedding of arsenic remediation through policy and economic incentives.

A recent review of decisions and actions by multiple actors in the past three decades (Das 2011) shows that the response to alarms raised by experts began with the creation by the state government, in 1983, of the first technical committee to understand the science and recommend actions. Subsequently,

in 1994, the state government created the Arsenic Task Force, with a goal to implement arsenic-remediation based on scientific knowledge, and through coordination of existing multilayered actors within existing institutional structures (e.g. the West Bengal government's Health Department, Public Health and Engineering Department, village panchayats, academic and research institutes, and international agencies interested in poverty alleviation through health and hygiene).

Between 1994 and 2007, the state government undertook technology selection and purchase decisions through public call of tenders for implementing arsenic-remediation, financed by both national and international institutions, and implemented and deployed by private technology-marketing companies and NGOs. The arsenic-remediation technical products are called Arsenic Treatment Units ("ATU"s) in the relevant literature in India. The deployment model was more of a linear expenditure model than a circular reinforcing investment model. In an expenditure model achievements are indicated not by a feedback loop but by a headcount measure of the supply side story: how many installations for how many beneficiaries (passive actors as opposed to users who are proactive actors). In an investment model feedback loops are important and the indicator is the return earned by initial spending to create a mechanism for self-financing through integration of the technology into user practices that come through preplanned social embedding. Official statistics using the headcount measure show 59% of the population has been provided with access to arsenic safe technological installations of various categories between 1984 and 2007 mobilizing national and international finance, 87 testing laboratories are spread over the affected districts. Furthermore, the proposed "master plan" design, to be effective from 2012, will cover 100% of the population.

Reality check shows otherwise. Tracing the event sequence over the past three decades, and a careful sample survey (Das 2011; Das and Roy 2011) shows that almost 95% of installed new arsenic remediation units/hardware (e.g. hand pumps with ATUs attached) are defunct, (i.e., not operational, wasted investments) due to lack of appropriate social engineering. Offsite private company/NGO operators had been initially contracted for a fixed period to undertake replacement of arsenic adsorbent-media and conduct backwashing of adsorbent columns. Their engagement was short-lived in the deployment model missing a feedback loop. So government implementers, engineers, and designers are now trying to follow the routine

age-old practices of centralized pressurized piped water systems or deep-aquifer tubewells, blocking their minds to new developments (Nelson and Winter 1982). However, both technological fixes are failing to gain user acceptance in practice. Apparent failure (because inadequately designed social engineering is not commonly understood or reported) of government-led contract programs has created a mind block among various social actors towards any future government-initiated business models relying on public private partnership (PPP). With the current mind block, users continue to be seen as "beneficiaries", not as customers, and integration with social practice is thrown by the wayside.

In summary, the dominant part of the socio-technical system in transition is gradually sliding back to offering the choice of drinking water from either the local arsenic-bearing hand tubewell (unacceptable), or remotely and unreliably tested deep tubewell (also unacceptable). We see public policy making a complete 1800 turn to near pre-1983 socio-technical regimes, with coevolution of public health policy and public health engineering driving to the same old dead-end. This can be identified as maladjustments that will aggravate crises.

Process analysis also shows that deployment efforts for arsenic remediation were not systemic, and ignored user practice integration and social embedding, in what appears to be a rushed attempt to get a quick solution through expenditure on hardware purchases and deployment. Users perceived the program and treated the new technology as user-unfriendly (Hossain et al. 2005). A small number of short term success stories do exist that include some social innovation through user participation as consumers, either through the leadership of the technology provider (e.g. Bengal Engineering College technology (Sarkar et al. 2008)) or at the initiative of individual champions. However, none of these niche experiments demonstrate systemic, planned social embedding. This lacuna might jeopardize transition to a lasting sustainable solution.

General principles of designing the technology solution

Before going into specifics, it is worthwhile to outline the general principles by which we proceeded to develop the technology solution, since these principles are applicable to other situations. These principles are based on analysis of a few decades our own cumulative experience and that of many others obtained through either first-hand discussion or studying the literature. We skip the details given the length-limit of this paper, and offer a summary

below.

We proceeded from three broad principles, summarized below, with their basis explained briefly. We assume that the technology is not being “supply driven” – i.e., it is not someone with a hammer looking for a nail, but is “demand driven” – i.e., the inventors and innovators are able to walk in the shoes of the ultimate end-users and customers, and try to address a problem perceived by the community members as significant.

1. The technology must be robust.

By this we mean that the inventors and innovators must apply the constraint that the technology will perform its intended task under stressful and difficult environmental and operating conditions encountered in the field (such as power blackouts and brownouts, dust, ambient heat and humidity, and being serviced by individuals with little formal technical training). This constraint of robustness must be applied right from the early stages of conceptualization and idea generation – so we don’t end up in a blind alley. Implied in this statement is the desire that the technology must perform at a level that is expected for first-world inhabitants. In other words, we should apply our best knowledge and creativity to ensure that we do not provide a lower service level to the poor people in the developing countries, by assuming that it would be “good enough” for them.

2. The technology must be locally affordable and culturally acceptable.

This is essential to ensure a financially viable technology in the long run. Only locally affordable technology will allow a sustainable solution that does not require continuous infusion of external subsidy or cash to keep it operational and make it available to millions of people. Furthermore, the technology must not run counter to local culture. In the ideal case, the invention will be adopted, without compromising its technical performance, to suit the culture and habits, and the inventors will not need to push to change the culture or even daily habits, for the invention to work.

3. The invention and innovation must be scalable.

In business language, “scalability” means the ability for the invention to be replicated and delivered to millions or even hundreds of millions of end-users. Many inventions that we now take for granted have gone through this process successfully – and many other inventions could not go to scale, and ended up just as curiosities. For an invention to go to scale, its bare cost must be at least 4 to 5 times lower than to its perceived monetary value to the end user. Only then there is a business case to be made for mobilizing finance capital, that is essential for large scale production and delivery of

the innovative product or service. We note that there are other aspects of scalability constraint. The invention must not rely on some unique material that is short supply; it must not produce waste products that are difficult to dispose of, or environmental damage that will be unacceptable when deployed on scale. If used on scale, the innovation must not have foreseeable unacceptable consequences in economic or social spheres.

Creating a niche for ECAR

The goal of our action research has been to develop a robust, locally affordable, and scalable solution (e.g. technology plus social innovation) to provide arsenic-safe water in contaminated areas. A few appropriate solutions exist for areas where suitable surface water is available for treatment (see Gadgil and Zaidman in this same volume). However, no suitable solution exists for areas in which surface water resources have been depleted, contaminated with toxic chemicals due to industrial and agricultural runoff, or are otherwise unavailable or undesirable. Thus our focus has been on creating, in a very short time, a niche for an arsenic remediation solution. To meet this need, Electrochemical Arsenic Remediation (ECAR) technology (discussed in more detail below) has been invented by Lawrence Berkeley National Lab (LBNL) and the University of California-Berkeley (UCB) and has been indigenously replicated in collaboration with Jadavpur University in Kolkata.

We start from the premise that both technology and society are important and interact in a complex process to deliver a socio-technical regime. Technologies function within a societal context (Rammert 1997). We understand that the development of technology involves technical engineering knowledge and prototype design in addition to “heterogenous engineering” (Latour 1987; Law 1987) - mobilization of resources, creation of social networks (e.g. sponsors, potential users, firms), development of vision to attract attention, construction of new markets, regulatory mechanisms (Geels and Schot 2011), and art of implementation (Das and Roy 2011). All these define a “configuration that works” (Rip and Kemp 1998). Success stories around a technology or hardware build on the process by which a socio-technical system is configured. Technical and social changes are engineered to align and fulfill a function. Thus the model of developing ECAR technology in a full solution involves a community of engineers (i.e. technological regimes) interacting with social groups (e.g. social scientists, users, policy makers, special interest groups, private investors, local NGOs,

people in local governance, and institutional structures emerged in past three decades) to form a socio-technical regime (e.g. Geels(2004)). To provide a social context, we have partnered with Amritabad High Madrasa School in the Murshidabad district of West Bengal.

The goal of our project is to accelerate the transition from the pre- and post-solution socio technical regimes. In this process we are co-creating a new technology, market, and user preference simultaneously, as discussed in previous research (Leonard-Barton 1988; Coombs 2001; Oudshoorn and Pinch 2003). To accelerate the process, the model, including ECAR technology, is slowly being exposed to various stakeholders in conjunction with a series of field trials under the careful protection of multiple dedicated actors recruited at strategic times (an entry timeline for major actors appears in Figure 1). Major actors are dedicated to producing a lasting solution and willing to invest resources in developing such a solution. The expected time lag between invention and commercialization using this strategy is 10 years (2005-2015). This project has been conceived keeping in mind the need to breakaway from lock-in affects of the past thirty years of experimentation in arsenic affected areas. Currently, we are simultaneously working on three distinct components: technology innovation, user integration, and social embedding. Up to 2009, the innovation phase for ECAR dominated, and from 2009 it is being supplemented by user integration and social embedding.

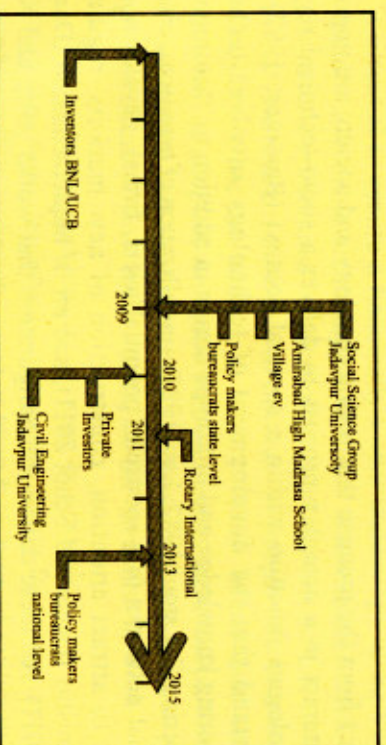


Figure 1: Entry timeline for multiple actors

The partnership with Amritabad High Madrasa School has led to a model of socio-technical system innovation through schools. The concept is simple. Schools have been identified as multiple poverty reducing service delivery

centers in India for quite some time now, (e.g., the government has sponsored quite successful mid-day meal programs to ensure nutrition and health to children and act as incentive to avoid drop out in schools). If arsenic safe water access installations are located within schools to deliver arsenic safe water to children and others (e.g. teachers and staff), user group integration can automatically emerge and multiply beyond school hours as well. By properly designing regulations, policy, and market, schools with arsenic safe installations can become "socio-technical system innovation centers" for replication to bring behavioral change that can sustain lasting transition in a social context. Existing programs can be leveraged – for example, in arsenic affected areas, unless mid-day meal programs are supplemented by arsenic safe water service provision, the health outcomes will be far from the target, resulting in a natural alliance. •

Technology Innovation: ECAR

Electrocoagulation (EC) is a method employed for treating polluted drinking water and wastewater for numerous contaminants (Vik et al. 1984; Chen 2004; Mollah et al. 2004; Holt 2005), including arsenic (Kumar et al. 2004; Parga et al. 2005; Gomes et al. 2007; Addy 2008; Zhao et al. 2010). Here we briefly describe the scientific underpinnings of Electrocoagulation Arsenic Removal (ECAR). A DC current is passed through contaminated water using an iron anode. Electrolytic oxidation of the sacrificial iron anode produces nano-scale particles of hydrous ferric oxide (HFO) in contaminated water. Contaminants form surface complexes on HFO, which has a high affinity for arsenic. Arsenic-laden HFO then aggregates to form a floc that can be separated from water. The only inputs required for ECAR treatment are ordinary mild steel plate electrodes and low voltage (< 3 V) electricity. During the ECAR process, trivalent arsenite (As(III)) is oxidized to pentavalent arsenate (As(V)). This is a key reaction, as As(III) does not adsorb as strongly as As(V) to mineral surfaces in natural waters (Manning and Goldberg 1997), making it difficult to remove without pre-oxidation to As(V) (Hering et al. 1996; Meng et al. 2000). Both forms of arsenic are present in appreciable quantities in contaminated groundwater.

ECAR has many advantages over other low-cost arsenic removal methods such as chemical co-precipitation with ferric salts and filtration through activated alumina or granular iron-based adsorbent media. These include:

- Higher adsorption capacity due to the much larger surface area of

- newly precipitated nano-scale particles
- Ability to oxidize and effectively remove As(III)
- No need to backwash media, (since media are removed by precipitation)
- No need for media regeneration, avoiding the need to handle strong acids or alkalies in the field
- Low maintenance needs (electrodes can be cleaned by automatically reversing the current direction during operation)
- Strong pH buffering ability (no need for pH adjustment)
- No need to import, manufacture, deliver, or handle media or chemical additives
- Very low production of waste sludge
- Amenability to automation

Challenges of ECAR include:

- Need for an electricity source
- Small size of HFO particles, requiring a separation step (unlike with larger media)

ECAR operates at low voltages ($< 3V$ in real groundwater with steel plates spaced 2 cm apart), easing electrical safety issues. Power can be supplied using grid, battery, or solar photovoltaic sources. The semi-batch process allows for electricity interruptions, and the equipment can be made robust against voltage surges, sags, and spikes. Arsenic-remediated water can be pumped and stored into an elevated delivery tank, preventing water supply disruptions during electricity outages.

We found that the very small size of HFO particles likely arises from surface poisoning due to high levels of phosphate and silicate ions found in groundwater (Gennuchten et al. 2011). These ions bind to the surface sites required for attachment by other HFO nanoparticles for particle growth, constraining the final particles to be sub-micron sizes. Particle separation using filtration requires material inputs and membrane maintenance. Separation by settling alone requires 1 – 2.5 days to achieve arsenic removal comparable to membrane filtration. However, we found that addition of a small amount of aluminumsulfate (e.g. alum) achieves rapid settling. Addition of 2 mg/L (as Al) was enough to speed up settling to < 2 hours in synthetic groundwater, and samples from West Bengal sites. Concentrations of 2 – 8 mg/L alum had comparable results, allowing for a factor of 4 increase in alum with no detrimental effect. After 2 hours of settling the water is visually very clear, with turbidity < 1 NTU.

It has been impressive and exciting to all stakeholders so far that the estimated operating cost of ECAR for removing 500 μg per liter arsenic from real groundwater to below 10 μg per liter, is about 1 paisa (US\$0.0002) per liter. We estimate that after including capital amortization, salaries of relevant personnel for maintenance, operations, and management, periodic arsenic-testing of treated water, and business overheads and margins, the final price would be about 20 paise (US\$0.004) per liter. All currency conversions here assume Rs. 50 to a dollar.

The mechanism of arsenic removal in ECAR is closely related to that of chemical co-precipitation with ferrous salts (as opposed to ferric salts) and Zero-Valent Iron (ZVI) filtration. In all three processes, Fe(II) ions are introduced into contaminated water that eventually form Fe(III) precipitates (e.g. HFO) used to adsorb arsenic. The delivery of Fe(II) ions differs in each case – in co-precipitation, it occurs through rapid dissolution of ferrous salts, in ZVI it occurs through natural corrosion of fine shavings of metallic iron, and in ECAR it occurs through accelerated corrosion of mild steel plates. Despite similarities, the ECAR process is advantageous due to:

- Simplicity of inputs (no need to import, manufacture, deliver, or handle ferrous salts or generate fine shavings of ZVI),
- Ability to sensitively control the rate of Fe(II) entering solution (allowing for a higher initial arsenic/HFO ratio, enhancing both HFO adsorption capacity and the ability to oxidize As(III) (Roberts et al. 2004)), and
- Rapid corrosion compared to ZVI (up to 100x faster).

A qualitative comparison of ECAR and other prominent arsenic remediation technologies is given in Table 1, as would apply to their use in a small community water center operated by a local person with high school education.

	Reliable AsI III/IV 10 ppb	Cheap	No Back Washing	No Media Replacement / Regeneration	Operator Skill
ECAR	✓	✓	✓	✓	✓
Ferric Salt Coprec/ZM	✓	✓	✓	✗	✗
Iron-based Media	✓	○	○	✗	○
Activated Alumina	○	✓	✗	✗	○
Anion Resins	○	○	✗	✗	○
Reverse Osmosis	✓	✗	✗	○	○
Piped Water Systems	○	✗	✓	✓	✓

Table 1: Technology comparison for use in a small community clean water center

Beginning in 2005, we created a series of bench-scale ECAR systems and tested performance in synthetic Bangladesh groundwater (SBGW), i.e., water matrix constituted to mimic groundwater in Bangladesh (Gennuchten et al. 2011). The use of synthetic groundwater allows for better prediction of field performance because phosphate, silicate, and arsenate (all present in groundwater) are known to influence the growth and structure of Fe precipitates (Waychunas et al. 1993; Rose et al. 1996; Doelisch et al. 2001) in addition to competing for sorption sites. The growth of Fe precipitates is highly relevant to the cost and complexity of separating Fe precipitates from water, because smaller colloidal particles are generally more difficult to remove. The rate and extent of As[III] oxidation may also be affected by groundwater composition. Using bench-scale systems, we were consistently able to reduce initial concentrations of As[V] and As[III] of up to 3000 µg per liter in SBGW to below 10 µg per liter, the WHO maximum recommended contaminant level.

To further test efficacy, we verified ECAR performance in real groundwater containing organic and inorganic matter that could potentially interfere with the process. In 2007 - 2008, we designed and successfully tested a continuous flow ECAR prototype to treat water from two arsenic-contaminated tube wells in Dhangahanga village near Dhaka, Bangladesh, (initial arsenic 200 and 250 µg per liter respectively) and nine arsenic-contaminated tube wells from three communes (Preaek Russei, Dei Edth, and Preaek Aeng) in Kandal Province, Cambodia (initial arsenic concentrations 80 – 760 µg per liter). The system was powered with a 12V car battery via a small constant-current circuit. A bench-scale system was also tested in Bangladesh in Jessore, Narayanganj, and Chandpur districts (initial arsenic concentrations 93 – 510 µg/L). In every case, we achieved final arsenic concentration below the WHO limit of 10 µg per liter, and in many cases less than 5 µg per liter. This demonstrated that ECAR treatment is effective in real arsenic-bearing groundwaters of South Asia.

In 2010, a 100 liter batch ECAR reactor was designed, built, and tested in Berkeley for removing arsenic from SBGW. The prototype (Figure 2a) comprises a cylindrical tank for dosing and mixing connected to a sedimentation tank for coagulant addition and solid/solution separation. The electrode assembly (Figure 2b) comprises 10 parallel interdigitated mild-steel plates (5 anode and 5 cathode) with alternate plates electrically connected. The configuration allows for easy reversal of current, allowing each plate to alternate between anode and cathode to minimize extensive rust build up

and passivation. The electrode assembly rests on a perforated non-conducting base plate. A DC motor attached to a small impeller continuously pushes water under a base plate and up between the electrode plates. The voltage across the electrodes was < 3V.

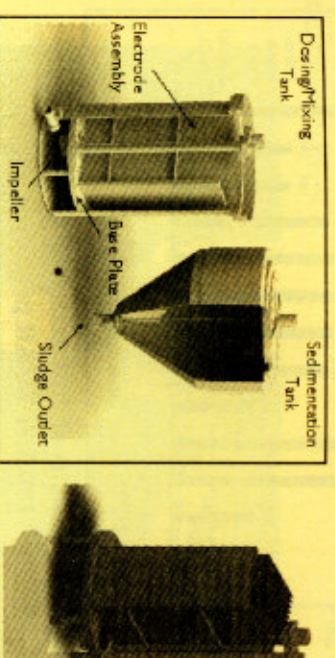


Figure 2: Schematic rendering of 100 liter batch ECAR prototype

In November – December 2010, we transported all equipment to West Bengal and conducted a successful 6-week field trial (2 weeks of operation) of the 100 liter reactor in West Bengal, India, at Amirabad High Madrasa School (~2500 co-ed students). During the field trial, we treated 1400 liters of arsenic contaminated water from three different tubewells used to supply drinking water to the School. Pre- and Post-treatment arsenic concentrations for each batch are presented in Figure 3. All but 2 of the batches were remediated to arsenic levels below 10 µg per liter. The two batches with slightly higher final concentrations (Test 1 and 4) were purposely undosed respectively with dissolved iron and added alum relative to effective lab tests. Both tests were repeated with correct dosing under the same conditions (Test 3 and 5 respectively) and reached final concentrations less than 10 µg per liter. Treated water was indistinguishable from commercial bottled mineral water in clarity, and less turbid than the original groundwater. We had no major operational difficulties or decreases in performance during the experiment, proving that ECAR electrodes will not passivate after a short run time in the field.

We have so far operated the replicated prototype in a batch mode, and transition to a continuous mode is planned in the near future. Design parameters of the continuous process will be determined after undertaking pilot scale research.

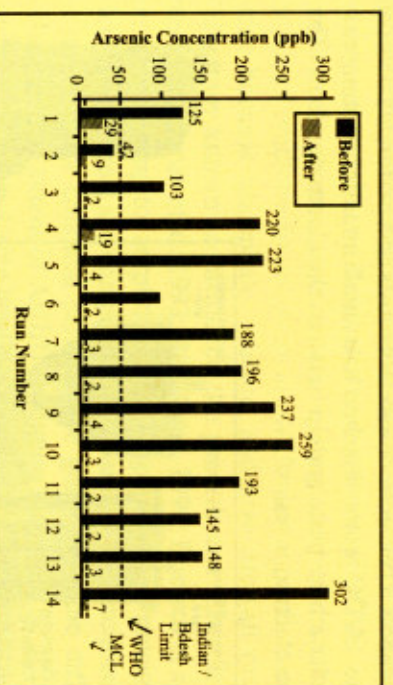


Figure 3: Results of 2010 technical field trial with 100 liter ECAR prototype

All arsenic removal technologies produce arsenic-laden sludge or waste that must be disposed of. The amount of sludge collected per 100 liter batch (including alum) is between 10 and 20g for initial arsenic concentrations of between 600 and 3000 $\mu\text{g/L}$. Leachates from waste sludge generated during batch reactor tests were prepared via a Toxicity Characteristic Leaching Procedure (TCLP) using US EPA Method 1311. The resulting leachate was analyzed for Ag, As, Ba, Cd, Cr, Hg, Pb, and Se metals and all were found to be well below regulatory limits (most were not detected). Arsenic in the leachate was 160 $\mu\text{g/L}$, well below the regulatory limits of 5000 $\mu\text{g/L}$. Thus ECAR waste sludge is not considered hazardous waste in the U.S.

However, previous studies suggest that leaching of arsenic may be enhanced in a landfill or hazardous waste site (Chosh et al. 2004; Delemos et al. 2006). Therefore alternative methods of waste stabilization should be explored. Banerjee and Chakraborty(2005) have demonstrated that preparation of briquettes, cement sand-mortar, and concrete with a similar arsenic-laden sludge mixed in at up to 10, 18, and 40% of volume respectively produced a TCLP leachate below the Government of India inland water discharge standards. Concrete used to stabilize arsenic-laden sludge could potentially be packed into roadways with minimal risk of arsenic leaching. To test this option, arsenic-laden sludge was generated using ECAR in SBCGW (estimated arsenic loading was 1.5% of sludge weight), and subsequently mixed into the aggregate of a Portland-cement concrete mixture, replacing 40% concrete by volume and 6% by weight. Two resulting 100g concrete cylinders were cast, cured for 7 days and then crushed to particles of < 9.5 mm diameter. A TCLP leachate preparation of the crushed concrete showed no detectable

arsenic via ICP-MS (detection limit 1 $\mu\text{g/L}$). Other tested metals (Ag, Ba, Cd, Cr, Hg, Pb, and Se) were either not detected or well below US EPA regulatory limits. This suggests that concrete stabilization may be a viable alternative to landfill disposal for ECAR, with adequate collection of sludge made possible in a business model that also has weekly service visits to the water-treatment centers.

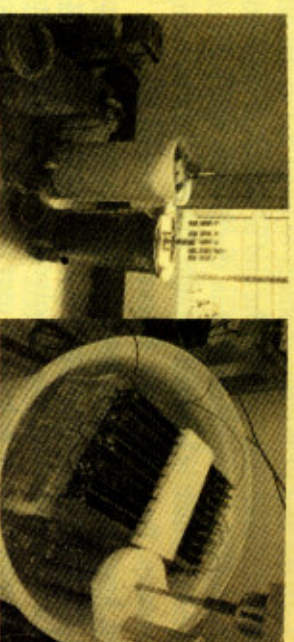


Figure 4: Indian built 100 liter ECAR prototype

In 2011, LBNL and UCB came into an agreement with Jadavpur University to replicate the 100 liter ECAR prototype. The fabrication and commissioning job was executed over three months at an engineering workshop in Howrah, West Bengal, using indigenous materials and accessories. On completion the 100 liter replicated prototype was field tested at the Amirabad High Madrasa School in December 2011, using local groundwater spiked with additional arsenic. This location bears good hydrogeological resemblance with the adjacent arsenic-affected Rajsahi District of Bangladesh. Four batches of local groundwater were remediated, following the procedures of the Dec 2010 field trial performed by the UCB team. Preliminary results show comparable performance as the prototype built and operated by the UCB team, including a post-treatment arsenic concentration less than 10 μg per liter (initial concentration range was 140 – 360 μg per liter).

Social innovation: user integration and social embedding

Social engineering for ECAR started with the technology inventors' initiative to identify and network with an independent social scientist with proven domain knowledge (Roy 2008) and understanding of the social context. Initial vision sharing among researchers from multiple disciplines started through meeting with experts. Most of the local actors subsequently were identified jointly by two team leaders. Multiple actors (listed in Figure 1) with proven track records of long term dedicated research interest on the

issue and an appreciation of lasting solutions became involved in their respective roles and began dedicated effort towards careful protection of niche. An NGO founded and operating in Amirabad village (BAJS-Amirabad) is an active participant in identifying the first incubation center and managing the community's expectation. The timing of inclusion of actors and role definition are part of the social innovation model. Niche managers are interacting with the rest of the stakeholders to align the social embedding process, which will dominate towards the end of technical innovation stage. Managing the incubators' expectations in the process has been one of the challenging event which is handled through frequent visit by technical and social innovators, free and frank discussions, vision sharing, resource mobilization, knowledge sharing about technology development pathways, conducting the technology development and testing in public space - all have played a very important role. Involvement of private investors at the niche development stage is helping in user integration through confidence building. Frequent networking with policy makers, implementers, and bureaucrats at the local level, including listening to their perception of past and future programs and sharing alternative socio-technical contexts are enriching the social embedding process.

Water and Sanitation Rotarian Action Group (WASRAG) under Rotary International joined in the ECAR team in 2011 to help in scaling up robust, scalable, low cost and sustainable technological innovation beyond the prototype, through show-case projects to attract competing private investors and help in market creation for a lasting solution. Once our 500 liter demonstration become operational, Rotary International may help in diffusion of the model beyond the current niche, and also help build cooperation with the government's policy makers and implementation planners.

Summary and Conclusions

We describe the social science context and stakeholder engagement process underway, even as we make progress with a series of successful technical field trials in West Bengal of ECAR technology for affordable arsenic-remediation of groundwater used for drinking. Technical innovation is sensitive to social context. Technical innovation of ECAR supplemented by social engineering forms the core of our model of technology maturation, field trials, stakeholder engagement, social embedding, and transfer to licensees for scale up. The technology and the approach for its social embedding are likely to be useful elsewhere in the region, (e.g., Nepal,

Bangladesh, Cambodia, Vietnam) affected with natural arsenic contamination of groundwater.

ECAR is promising for arsenic remediation in poor rural parts of South Asia. It is technically highly effective in reducing arsenic and has locally-affordable cost per liter; the technology has very few moving parts; it is easy to operate and maintain and uses indigenous materials; no toxic or corrosive chemicals are required for any media-regeneration; and the bound arsenic in the small amount of resulting sludge is easy to immobilize. Furthermore, ECAR technology is easily scalable can be easily maintained by trained rural people.

ECAR technology and its attendant social innovation for embedding offers hope for achieving lasting solution to the grave crisis in arsenic affected areas of rural India, Bangladesh, and elsewhere

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